6 Damage Patterns

INTRODUCTION

This chapter provides an overview of the macroseismic effects of the Bhuj earthquake. Such information is useful for several reasons. First, direct information about the vulnerability of structures to strong ground motion is useful for assessing, and perhaps mitigating, the hazard posed to similar structures by future large earthquakes. Secondly, given the paucity of instrumental recordings of the Bhuj earthquake, macroseismic data can provide useful information about the spatial variation of ground motions. Finally, detailed damage assessments for this earthquake can be compared to available accounts of historic earthquakes in India and other similar tectonic regimes around the world. These comparisons will provide additional insight into the magnitude of important earthquakes for which there are few or no instrumental recordings.

The Bhuj earthquake is of particular interest because of the possibility that it represents an analog for the principal New Madrid (central United States) earthquakes of 1811-1812. The Bhuj earthquake occurred much closer to an active plate boundary than did the New Madrid events, and the Bhuj earthquake might therefore be considered a plate boundary-related event. However, in both cases, the regions primarily affected by the earthquake are stable continental interiors with low attenuation.

A quantification of damage patterns, such as that presented in this chapter, can provide useful insight into the attenuation and frequency content of ground motions, which may in turn be useful in resolving whether the Bhuj earthquake should be considered interplate or intraplate for the purpose of data classification.

This chapter combines two different approaches to quantify macroseismic effects of the Bhuj earthquake. First, a large-scale map of intensities was compiled based on media accounts. Second, ground-level surveys of damage in towns and villages across the epicentral area by the India-U.S. Geotechnical Earthquake Engineering Reconnaissance Team were synthesized. This approach provides both coarse- and fine-scale overviews of damage, as well as an opportunity to compare detailed ground-based intensity results to a "broad brush" intensity value determined from one or a small handful of media accounts for any one location.

ESTIMATING INTENSITIES FROM NEWS ACCOUNTS

A full compilation of shaking effects for the 2001 Bhuj earthquake will require detailed survey, and will not be available for some time. However, abundant news accounts were available in the immediate aftermath of the earthquake. Accounts from Indian and U.S. newspapers and from the World Wide Web were collected and interpreted to obtain Modified Mercalli intensities (MMI) at over 300 locations throughout India and Pakistan. Maps of the resulting intensity distribution are shown in Figure 6-1. To generate these maps, a simple mathematical approach was used to interpolate between locations with known intensity values. Away from the constrained data points, the maps may be inaccurate due to variations in shaking intensity with geologic site conditions.

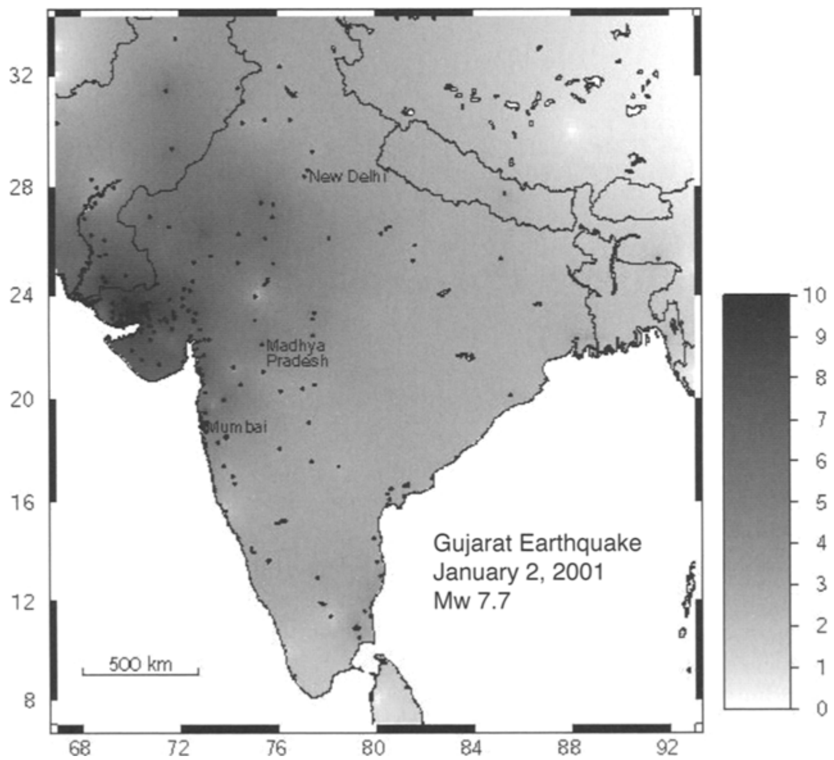

Figure 6-1. Overview of modified Mercalli intensity across Indian subcontinent. The scale (right side of figure) was developed from data from recent earthquakes in California, from which quantitative ground motions are used to estimate "instrumental intensity" based on established relationships between MMI and ground motion parameters (Wald et al., 1999). Figures 6-1 and 6-2 are generated directly from estimated MMI values.

The scale of the MMI maps is defined so that the dark shading saturates around MMI IX, a level of shaking corresponding to extreme damage or collapse of vulnerable buildings, but not to collapse of modern, earthquake-resistant engineered structures. Because of the vulnerability of buildings in the Kachchh region, very few MMI values in excess of IX have been assigned. On the MMI scale, significant liquefaction effects generally define an intensity of at least VIII, although the threshold for liquefaction triggering is likely closer to VII (e.g., Keefer, 1984; Dave Wald, personal communication, 2001). The dark gray in Figure 6-1 indicates the areas over which light damage, such as cracks in walls, occurred. In some cases, media reports provide some information that can be used to assess the extent of damage, such as whether "all," "most," or "some" buildings collapsed. But when MMI values are assigned based on media accounts, the usual practice (followed here) is to assign a value based on specific reports of damage, even if it is not known how representative such damage is. A detailed account of the intensity assignments, and the accounts on which they are based, is given in Hough et al. (2002).

Figure 6-1 provides an overview of shaking effects of the Bhuj mainshock across the subcontinent, illustrating the vast extent of the area over which this earthquake was felt. Shaking was felt as far as 1500 km east of the epicenter, although there were also sites on the subcontinent where it was not felt. The general distribution of shaking reveals a couple of interesting results:

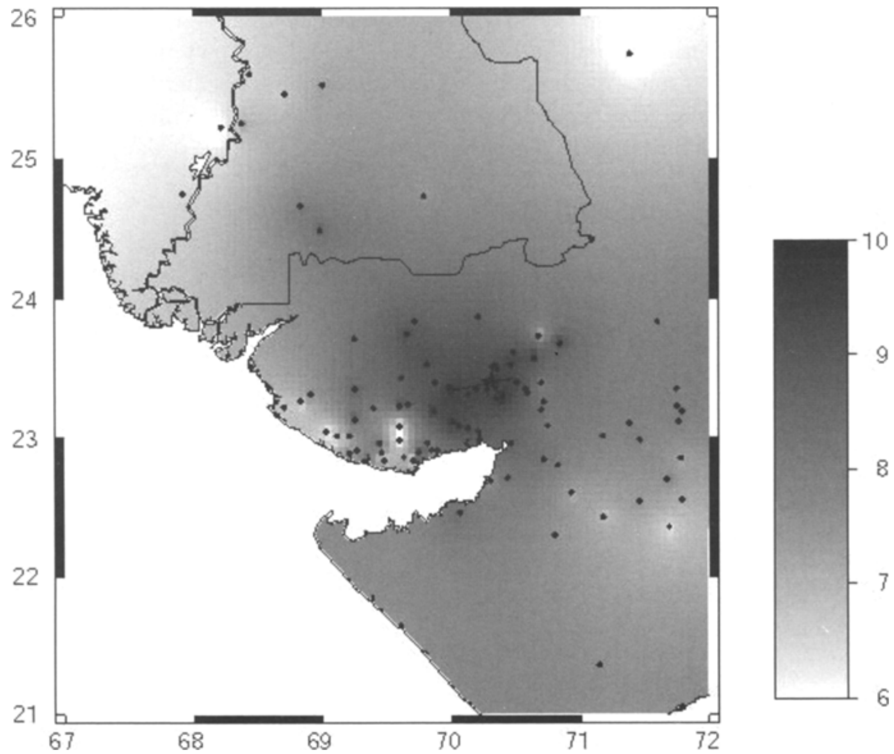

Figure 6-2. Overview of instrumental intensity in Kachchh region. Black line is drawn along the approximate strike through the epicenter over the lateral extent of the estimated fault rupture plane.

1. Ground motions were apparently amplified at sediments sites south along the coast toward Mumbai and to the east/northeast along river valleys.
2. The felt extent coincides quite well with the extent of the subcontinent. This provides evidence for earlier suggestions that higher-mode surface (L_g) waves propagate efficiently through intraplate regions until they encounter substantial complexity in crustal structure near plate margins. As suggested by Hanks and Johnston (1992), these waves may account for the enormous areas over which large (M>7-7.5) intraplate earthquakes are felt. Indeed, both the Bhuj earthquake and the largest New Madrid mainshocks were felt at distances of 1500 km, and caused light damage at sediment sites ~500 km from the source (Hough et al., 2002).

Focusing on the Kachchh region itself (Figure 6-2), the relatively high intensities at sites around the rim of the Gulf of Kachchh suggest possible sediment-induced amplification in the soft sediments at these sites. Other patterns of damage distribution are also evident: Damage is not distributed uniformly about the lateral extent of the source zone (the east-west extent of which is shown by the line in Figure 6-2). Rather, damage was relatively low to the southeast of the (presumed) causative fault. Damage was highest on the hanging wall (i.e., the block of earth overlying the dipping fault plane, this block is located south of the line in Figure 6-2) and immediately west of the source zone. There is also a suggestion that, away from the source zone, shaking was relatively stronger toward the north than to the south. These patterns are broadly consistent with expectations for a south-dipping blind thrust rupture with (primarily) northward directivity. However, the high intensities north of the rupture may also reflect sediment-induced amplification and liquefaction in the northern Kachchh region.

DAMAGE PATTERNS FROM FIELD RECONNAISSANCE

Media-based intensity surveys typically yield only a single intensity value for each city. It is often impossible to tell whether the damage described in a news article is representative of that region. Detailed ground-based surveys, on the other hand, are able to assess not only the overall damage level, but also map out detailed variations.

Damage patterns across the region were evaluated using field observations made by the India-U.S. Geotechnical Earthquake Engineering Reconnaissance Team. The Bhuj earthquake has been estimated to have destroyed about 348,000 buildings in the area, and damaged another 844,000 (Bendick et al., 2001). These affected buildings can be broadly characterized as follows:

- Nonengineered residences constructed of load-bearing masonry walls that support a roof of tile or reinforced concrete. Masonry is typically brick or stone, and the structures are typically one to three stories in height.
- Reinforced concrete frame buildings with nonstructural curtain infill walls of unreinforced masonry (typically brick or cinder block).

Masonry is by far the most prevalent type of construction in the region, and the discussion of damage patterns that follows is focused principally on the performance of these structures.

Reconnaissance of the performance of masonry buildings was performed across the region expected to have undergone strong shaking. Most development in the region has occurred within small villages, and the performance of structures within a village was broadly categorized using the scheme depicted in Table 6-1.

A synthesis of the damage categorization is presented in Figure 6-3, where the size of the squares indicates the level of damage (i.e., largest squares for Category E damage, smallest for Category A damage). The data in Figure 6-3 are based both on field observations and study of low altitude aerial photographs taken within two weeks of the earthquake.

Table 6-1. Damage classification scheme for unreinforced masonry buildings in local regions.

URM Damage	Collapse Frequency
A	No collapse
B	Minor (<10%) collapse
C	Moderate (10-50%) collapse
D	Significant (50-90%) collapse
E	Complete (> 90%) collapse

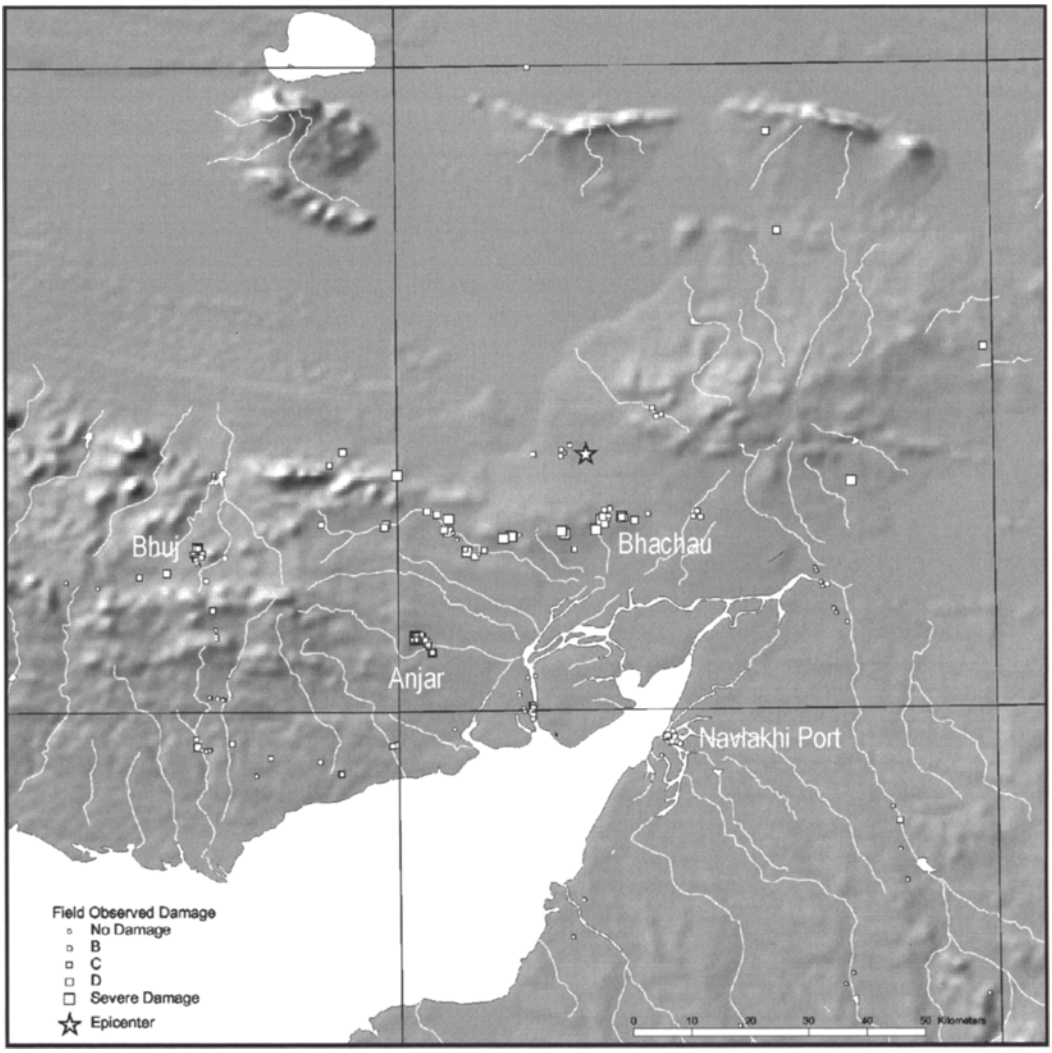

Figure 6-3. Damage distribution to unreinforced masonry buildings in epicentral area as determined from ground observations.

Damage was generally severe in the area immediately south and west of the epicenter, within an area approximately defined by a triangle with corners at the relatively large cities of Bhuj, Anjar, and Bhachau. Much of this area was apparently on the hanging wall of the ruptured fault segment, and would therefore be expected to have experienced strong shaking. The severity of damage decreased notably in the villages west of Bhuj and south of Anjar, which are likely located off of the hanging wall. Some locally concentrated damage did occur at other sites not on the hanging wall. One such site is Navlakhi Port, which is located along the margin of the Gulf of Kachchh and is underlain by soft marine sediments. Interestingly, several other ports, including Kandla Port and Adani Port, were closer to the seismic source zone, yet experienced less damage than Navlakhi Port. Further discussion of the damage at these ports is provided in Chapter 8, Ports.

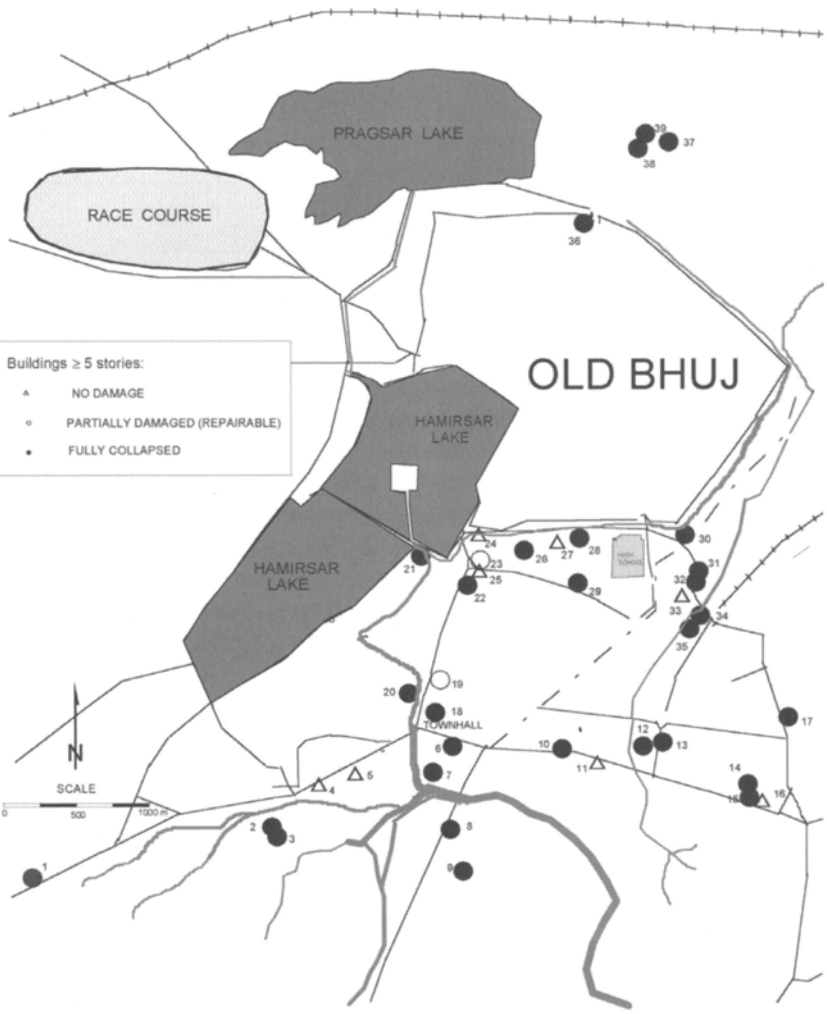

Figure 6-4. Map of Bhuj showing locations of buildings with 5 stories or more.

Damage patterns were also examined locally within the three largest towns in the epicentral area: Bhuj, Bhachau, and Anjar. Bhuj is the largest of these, with more than 100,000 residents. Buildings in the core of the town ("Old Bhuj") are almost exclusively of unreinforced masonry construction that dates from the 1700s. These structures were devastated by the earthquake (i.e., Category E; refer to Table 6-1). Interestingly, masonry construction within the Bhuj environs, but outside of Old Bhuj, performed markedly better, generally sustaining Category B-C damage. Outside of Old Bhuj, there are a number of tall (3- to 10-story) reinforced concrete frame buildings scattered throughout the city. The locations and degree of damage of all buildings with 5 or more stories are shown in Figure 6-4. Over 75 percent of the tall buildings in Bhuj collapsed, which is a significantly higher damage rate than the shorter, URM buildings in the area. While information on the geology of Bhuj is not available, rock outcrops are visible at many locations throughout the town, and significant depths of sediment appear unlikely.

Figure 6-5. Aerial photograph of Anjar showing nearly complete devastation on left side of photograph and relatively modest damage to the right. Limited ground surveys suggested that in portions of the city, a north-south trending topographic rise separated the two damage zones, with the light damage occurring above the rise and the heavy damage below it. (2/12/01, N23.11332, E70.02715)

Two factors may contribute to the observed concentration of damage in tall buildings in Bhuj. First, reinforced concrete construction is pervasive among tall buildings and relatively rare for short structures, which are generally of unreinforced masonry construction. The reinforced concrete construction, which is generally of poor quality, may have less seismic resistance than unreinforced masonry construction. Second, ground motions in Bhuj may have been richer in the period range of the relatively tall frame buildings (estimated as T^{a} 0.3-1.0 s) than the periods of the shorter, masonry wall buildings (estimated as T^{a} 0.1-0.3 s). If true, this feature of the ground motion is more consistent with the expected frequency content of interplate earthquakes (for which the mean period would be expected to be on the order of $T_m{}^{a}$ 0.5 s per the attenuation relation of Rathje et al., 1998) than intraplate earthquakes (for which $T_m{}^{a}$ 0.25 s would be expected, per Rathje et al., 1998).

Detailed reconnaissance of damage was also performed in Bhachau and Anjar, which are relatively small towns of population approximately 50,000 and 20,000, respectively. Construction in both towns consists principally of unreinforced masonry. Damage in Bhachau was nearly complete (Category E), both in flat areas possibly underlain by sediments and on ridgelines underlain by rock. Strongly localized damage was observed in Anjar. A topographic rise striking approximately north-south through the city separates regions with relatively heavy damage (Category E) and light damage (Category C-D), with the heavy damage occurring to the east at the low end of the rise (Figure 6-5). Information on the age of construction and the geologic conditions in the heavily and lightly damaged portions of Anjar are not available at this writing.

COMPARISON OF DAMAGE PATTERNS FROM FIELD OBSERVATION AND PRESS REPORTS

The intensity map (Figure 6-2) and the synthesis of ground-based observations of damage intensity (Figure 6-3) enable a comparison of damage assessments from press reports and field observation. Both clearly show a concentration of damage in the area south and west of the epicenter—across the hanging wall of the assumed fault rupture plane—and both suggest similar levels of near-source ground motions.

The distribution of damage revealed in the two approaches is also generally consistent. Both show a rapid reduction of shaking intensity to the west of Bhuj, which is a developed area with a significant number of observation points in both surveys. Both field observation and media reports show a general reduction of intensity to the east of Bhachau, although there are few observation points in this relatively undeveloped region. One interesting inconsistency is the region south of Anjar on the north shore of the Gulf of Kachchh, where ground surveys indicate only minor to moderate damage, while the press reports indicate violent shaking along the coastline. This discrepancy may reflect the noted limitation of assigning MMI values based on media accounts of damage that might not be representative of the region. In this case, press reports focused on a small number of cases of liquefaction along the coast that, it appears, were not triggered by ground motions of sufficient intensity to cause widespread structural collapse.

There are few ground-based observations in the Great Rann of Kachchh (north of the epicenter), hence the reduction of shaking intensity with distance to the north is unknown from ground surveys. Only press reports enable this variation in intensity to be established, although in many cases these are based only on observed liquefaction, which is a different indicator of shaking than is structural damage. As noted previously, some have suggested that liquefaction can occur for MMI intensity values less than VIII; hence it is possible that the intensity assigned to this area is too high.

CONCLUSIONS

The Bhuj, India earthquake was, unfortunately, a lost opportunity for the collection of much-needed strong motion data from a large magnitude, possibly intraplate earthquake. However, useful insights into regional and local variations of ground shaking can be gained from careful study of damage patterns.

The data compiled in this study indicate high intensities over the hanging wall of the presumed dipping fault plane, high intensities north of the seismic source that might be influenced by northward directivity effects, and locally high intensities around the margins of the Gulf of Kachchh that might be affected by sediment amplification. The attenuation of intensity with distance from the source is greater to the east than to the west for unknown reasons. The overall size of the high intensity zone is comparable to that from the New Madrid earthquake. Our results suggest that, regardless of the source setting, the Bhuj earthquake generated ground motions that appeared to have attenuated in a manner consistent with intraplate regions.

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